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CARBON AND NITROGEN ABUNDANCE DETERMINATIONS FROM TRANSITION LAYER LINES

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ABSTRACT

For red giants we find a smooth increase in the nitrogen to carbon abundance ratio for increasing B-V as is expected for the first dredge up phase when the outer convection zone deepens. We find an average increase in the nitrogen to silicon ratio for B-V $\sim$ 0.6 which surprisingly goes back to almost solar values for cool giants with B − V $\sim$ 1.0. It looks as if Si would be enriched for deeper mixing contrary to expectations from standard evolution theory.

Key words: Transition Layers, Giants, Carbon-Nitrogen Abundances.

1. INTRODUCTION

In 1981 (Ref. 1) Luck and Lambert found that in supergiants and Cepheids the element abundance ratios of nitrogen to carbon were enhanced while the sum remained constant. At the same time they found that the C^{13}/C^{12} ratio was also increased as expected if mixing in the stars had brought CNO cycle processed elements to the surface. In 1981 Lambert and Ries (Ref. 2) found the same situation for giants with B − V $\gtrsim$ 0.65. In both cases they found stronger enrichments than expected from standard evolution theory. These element abundance determinations applied spectrum synthesis to reproduce the molecular bands of CN, C_2, and NH. For stars with somewhat higher temperatures the infrared C and N lines were studied. Spectrum synthesis of molecular bands requires a good understanding of the temperature stratification near the temperature minimum, which may be somewhat uncertain. The infrared lines originate from rather high excitation levels and are therefore vulnerable to non LTE effects. It therefore seems good to verify the peculiar CN abundances in giants and supergiants by an independent analysis which is provided by the emission lines of the transition layers between stellar chromospheres and coronae.

2. METHOD OF ANALYSIS

2 1 Theoretical background

In an earlier paper we investigated the energy equilibrium in the lower transition layer with $30,000K < T < 1 \cdot 3 \cdot 10^5 K$. The energy input E_{in} per cm^3 and sec is supposedly due to the damping of a mechanical energy flux F_m. which means

$$E_{in} = -\text{div } F_m = -\frac{d\,F_m}{dh} = +\frac{F_m}{\lambda} \qquad (1)$$

where λ is the damping length λ may vary with height h in the atmosphere. Choosing T (h) as the independent variable we approximate the height dependence of λ by

$$\lambda = \lambda_o \cdot T^\alpha \qquad (2)$$

where α is a parameter which can be determined from the emission line fluxes of lines originating at different temperatures (Ref. 4). The energy loss is due to radiative losses E_{rad} per cm^3 and sec which in this temperature range can be approximated by

$$E_{rad} = \frac{d\,F_r}{dh} = n_e^2 \cdot B \cdot T^\beta \qquad (3)$$

with $\beta \sim 1.9 \pm 0.1$ and B is a constant. From $E_{rad} = E_{in}$ we derive for the temperature stratification (Refs. 3, 4)

$$T^{\beta+\alpha-2} = \frac{F_m}{\lambda_o} \frac{k^2}{B} \frac{1}{P_e^2} \qquad (4)$$

and

$$\frac{dh}{d \ln T} = \frac{(\beta + \alpha - 2) \cdot R_g \cdot T}{2\mu g_{eff}} \frac{1}{(1 - \frac{H}{2\lambda})} \qquad (5)$$

The surface fluxes F_L of optically thin emission lines are given by

$$F_L = C(L, T) \cdot A(el) \cdot \int_{h_1}^{h_2} n_e^2 dh = C(L, T) \cdot A(el) \cdot E_m(T) \qquad (6)$$

where C(L, T) depends on the collisional excitation cross section for the upper energy level of the line transition (L stands for line), A(el) is the element abundance relative to hydrogen of the line emitting element and $E_m(T) =$

$\int_{h_1}^{h_2} n_e^2 dh$ is the socalled emission measure. The integral has to be extended over the height interval over which the line is emitted, which corresponds to an interval in height over which the temperature changes by approximately a factor of two or over which $\Delta \ln T \approx 0.7$

Comparing the line fluxes of two lines of a given element, for instance, the line flux of the C II lines at 1335 Å which originate at a layer with an average temperature around $T_1 = 35,000K$ and the C IV line fluxes originating at an average temperature around $T_2 = 10^5 K$ we find

$$\frac{F_L(1335\text{Å})}{F_L(1550\text{Å})} = \frac{C(1335\text{Å}, T_1)}{C(1550\text{Å}, T_2)} \cdot \frac{E_m(T_1)}{E_m(T_2)} \quad (7)$$

With

$$\frac{E_m(T_1)}{E_m(T_2)} = \left(\frac{T_2}{T_1}\right)^{-(\beta + \alpha - 1)} \cdot \frac{\varphi(T_1)}{\varphi(T_2)} \quad (8)$$

From the study of many main sequence stars and giants we find empirically the relation

$$\frac{E_m(T_1)}{E_m(T_2)} = \left(\frac{T_2}{T_1}\right)^{-1.2 \pm 0.2} \quad (9)$$

fits the observations best. Writing $\varphi(T_1)/\varphi(T_2) = \left(\frac{T_2}{T_1}\right)^{\gamma}$. We thus obtain $\beta + \alpha - 1 + \gamma \approx 1.2 \pm 0.2$.

We can then determine the temperature dependence of the emission measures for the stars under investigation. Using solar element abundances we have plotted in figure 1 left and center part, the emission measures for main sequence and luminosity class IV stars as derived from the transition layer emission lines of C II, C IV and N V (1240 Å) originating at $T_3 = 1.5 \cdot 10^5 K$ as a function of the average temperature of the layer in which these lines originate. Within the expected measuring uncertainty ($\gtrsim 25\%$ for each line) these emission measures fall very well along the line given by equation (9). For our adopted solar Si abundance of log $(Si/H) = -4.4$ the emission measure calculated from the Si II lines at 1400 Å (formed at $T_4 \sim 75,000K$) by means of the C_L (1400 Å, T_4) which are given by Jordan and Brown (Ref. 5) came out too large which might indicate a large Si abundance However Si III lines often give too small emission measures. This problem was discussed earlier by Hartman et al. (Ref. 6). It is suspected that the $C_L(1400\text{Å}, T_4)$ are in error. We have applied an empirical correction of $\Delta \log C_L(1400, T_4) = +0.5$. This correction puts the emission measures for the Si IV lines on the same straight line with the other emission measures for all main sequence stars.

2.2 Abundance determinations for giants and supergiants

Comparing now surface line fluxes for different lines we find for instance

$$\frac{F_L(N \text{ IV})}{F_L(C \text{ IV})} = \frac{C(1240, T_3)}{C(1550, T_2)} \cdot \frac{A(N)}{A(C)} \cdot \frac{E_m(T_3)}{E_m(T_2)}$$

$$= \text{constant} \cdot \frac{A(N)}{A_\odot(N)} / \frac{A(C)}{A_\odot(C)} \cdot \frac{A_\odot(N)}{A_\odot(C)} \cdot \frac{E_m(T_3)}{E_m(T_2)} \quad (9)$$

With the ratios of the emission measures known from equation (8) and the ratios of the $C(L, T_i)$ known from atomic physics (Ref. 5) the relative abundances of the elements as compared to solar abundances can be directly determined from the measured ratio of the surface fluxes F_L (which is of course the same as the ratio of the observed fluxes f_L).

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We use a graphical method: we calculate $\log \frac{A(N)}{A_\odot(N)} \cdot E_m(T_3)$ and $\log \frac{A(C)}{A_\odot(C)} \cdot E_m(T_2)$ from the C IV lines as well as $\log \frac{A(C)}{A(C_\odot)} \cdot E_m(T_1)$ from the C II lines using equation (6) for the different elements These quantities are plotted as a function of log T_i For solar abundances they should fall on a straight line determined by equation (9). For non solar abundances the deviations from this relation show directly the abundance differences as compared to solar abundances.

In figure 1 (right hand part) we show the results for some supergiants which have also been studied by Luck and Lambert (Ref. 1) For these stars the values of $\log \frac{A(el)}{A_\odot(el)} \cdot E_m(T_i)$ indicated by the symbols do not follow a straight line. We draw the best fit line with the temperature exponent -1.2, as given by equation (9), through the carbon points. The deviation of the N (V) point from this line yields directly the $\Delta \log N/C$ as compared to solar abundances. In the same way we can read off the $\Delta \log \frac{C}{Si}$ which for all these stars is negative. We thus see directly the depletion of carbon and the enrichment of nitrogen in these stars as compared to the Si abundance.
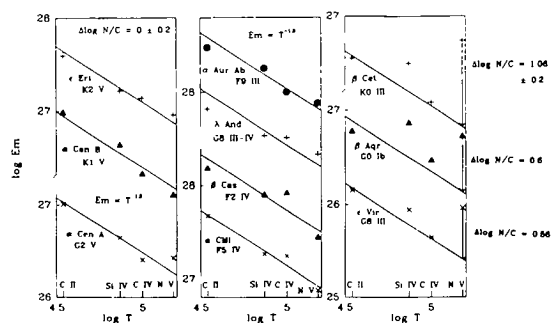

Figure 1. The temperature dependence for the emission measures of solar abundance main sequence and luminosity class IV stars is shown left hand and center. We generally find Em $\propto T^{-1.2 \pm 0.2}$ In the right hand figure we show the apparent emission measures for some giants and supergiants obtained by assuming solar abundances the apparent excess in the emission measures for the Si IV and N V lines is due to larger abundance ratios N/C and Si/C. For increased abundance ratios as shown on the right hand side, the emission measures agree with the $T^{-1.2}$ relation

3 RESULTS

3 1 The changes in the nitrogen to carbon abundance ratios

In figure 2 we compare the values $\log \frac{N}{C} - \log \frac{N}{C}$ for stars for which element abundances were determined by Lambert and collaborators by means of photospheric analysis with the abundance ratios determined from the transition layer emission lines. Within the limits of error we find very good agreement, though the abundance changes found by us are somewhat smaller ($\Delta \log \frac{N}{C} \sim -0.2$) than those found by Luck and Lambert.
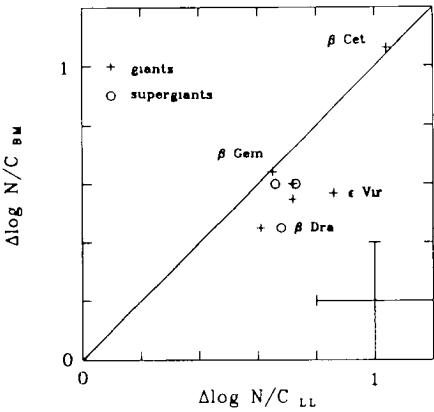

Figure 2 The photospheric excess abundance ratios, as compared to solar abundance ratios of nitrogen to carbon, obtained by Lambert and Ries 1981 and Luck and Lambert, are compared with the ones found from the transition layer lines. Within the limits of error for both studies (shown at the lower right corner) the agreement is quite good

In figure 3 we have plotted the $\Delta \log(N/C)$ as a function of B-V for all the giants studied by us. For B $-$ V $>$ 0 6 we find a slow increase in $\Delta \log \frac{N}{C}$ as expected for mixing by a deepening outer convection zone when the stars expand and become cooler. We find some stars which do not strictly follow this trend. Several of these have very weak and ill defined emission lines
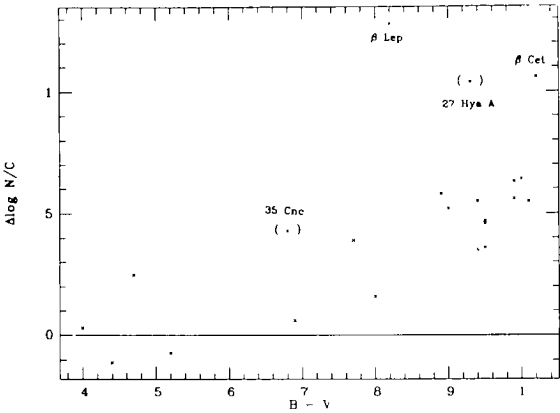

Figure 3 The excess abundance ratios of nitrogen to carbon as compared to solar abundances are shown for giants as a function of their B-V colors. The nitrogen to carbon ratio increases smoothly for cooler stars

3.2 The changes in the nitrogen to silicon abundance ratios

From standard stellar evolution theory we do not expect to see any changes in the silicon abundances when the stars evolve to become red giants. We should therefore be able to read off directly the increase in nitrogen abundances from the abundance ratio N/Si Unfortunately the Si IV lines are generally weak and not very well defined. They sometimes appear to be blended with neighboring, unidentified lines The results discussed here are therefore generally less reliable than those discussed in the previous section
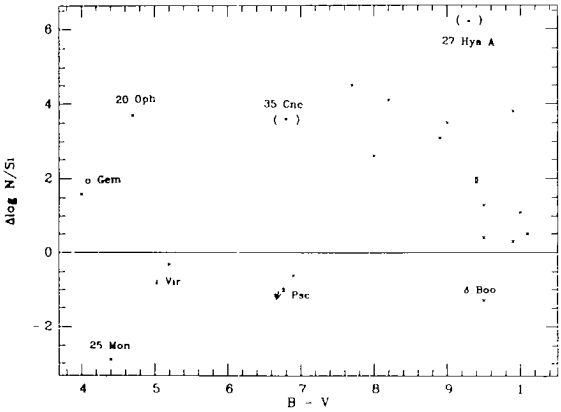

Figure 4 The excess abundance ratios of nitrogen to silicon, as compared to solar ones, are plotted as a function of B-V for the stars studied here A decreasing ratio seems to be indicated for the cooler stars but is hard to understand theoretically Perhaps the Si IV lines are blended with other lines

In figure 4 we show the changes in the N/Si abundance ratios as a function of B-V We do not see the smooth increase expected according to figure 3. The N/Si ratio appears to increase at B $-$ V $\sim$ 0.6 but then decreases again for cooler stars. It seems that the silicon abundances increases even more than the nitrogen abundances Since the Si IV lines behave somewhat unusual it is not impossible that the ionization and excitation conditions for these lines could change or that a blend with an unknown line could lead to false results Perhaps a blend with the semi-forbidden O IV] line at 1402 Å could cause the problem
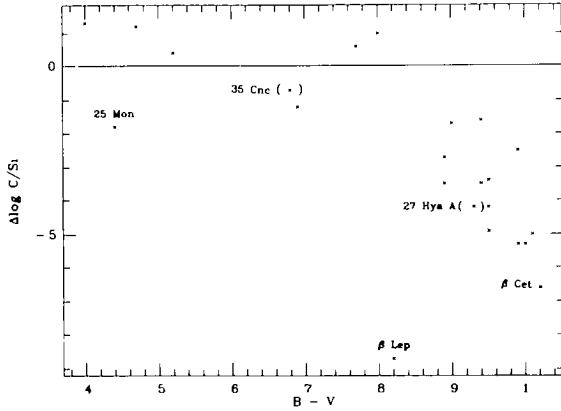

Figure 5. The abundance ratios of carbon to silicon as compared to the solar ones are shown as a function of B-V The decrease of carbon abundances for cooler stars is obvious. If the Si IV lines appear too strong because of blending the actual decrease of the carbon to silicon ratio will be less steep than seen here.

In figure 5 we show the ratio of $\frac{C}{Si}$ as a function of B-V. We see the decrease of the carbon abundances for the cooler stars as expected if CNO processed material is mixed to the surface. The decrease is steeper than expected probably due to the same increase in the SiIV line strengths as discussed in the previous paragraph.

4. SUMMARY

We have shown that relative element abundances can be determined from the emission line fluxes of lines originating in the lower transition layers. We confirm the increase in the $\frac{N}{C}$ ratio for cool stars found earlier by Luck and Lambert and Lambert and Ries.

Our method of analysis offers a simple way to determine $\frac{N}{C}$ ratios for all stars with transition layer emission lines.

ACKNOWLEDGEMENT

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